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A methodology for spatial modelling of energy and resource use of buildings in urbanized areas

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Abstract: *This paper presents and discusses a methodology for modelling energy and resource use of urban building stocks. The methodology integrates and further develops methodologies for energy, carbon and resource use analysis on building stocks with the aim of applying these to a case study of the City of Gothenburg, Sweden. Integrating geographical information systems (GIS) in the methodology for modeling of the building stock, allows assessment of the contribution and effect of various strategies to meet environmental goals for municipalities, portfolio owners, such as housing associations and institutional investors. The methodology identifies different development strategies including various options for refurbishment, add-on and new construction, which are evaluated with respect to their potential environmental impacts related to the life-cycle of the building, including construction and end-of-life options.*

Building stock modelling, LCA, EPC, GIS, carbon emissions, strategies

Background

The building sector is responsible for significant use of resources and energy and in many regions this sector also contribute significantly to climate impact since the energy carriers used for heating and cooling are often provided from fossil fuels (e.g. natural gas based electricity for heating). The European Energy Performance of Buildings Directive adopted a set of efficiency standards for both new and existing residential and commercial buildings [1, 2] and Swedish governmental policy aims at considerable reductions in energy use by 2020 and 2050 [3, 4]. However, it is not clear what robust options for transforming the building stock towards meeting the energy and carbon goals are, i.e options which do not result in lock-in effects. In addition, a thorough analysis of such options should take into account environmental impacts considering the entire life-cycle of the buildings to avoid sub-optimized development strategies when only emissions during the operation of buildings are considered. Thus, the aim of the work presented in this paper is to develop a methodology, which can analyse possibilities and potential for reducing the environmental impact of urban building stocks. This is done by linking building stock modeling (BSM), Life cycle assessment (LCA) and Geographical Information Systems (GIS) so as to form an integrated methodology which take into account direct energy use and emissions together with life cycle effects of the building materials as well as providing a spatial description and illustration of the impact of various scenarios for (energetic) refurbishment, densification and replacement in the building stock.

Building stock modeling (BSM) refers to the different modeling techniques used to model the energy demand for parts of, or the entire building-stock in a specified area. BSM is applicable for the *existing building stock* but can be applied to assess the impacts resulting from future development options of the *future building stock* as well, considering various scenarios for refurbishment, densification and replacement. The different modeling techniques commonly employed to assess the energy use of buildings are described in [5]. According to the classification in [5], so-called bottom-up engineering models are the only ones suited to evaluate the impact of new technologies and model interaction between end uses. Such models are based on representative buildings, i.e. heat transfer and thermodynamic relationships are used to explicitly account for the energy use of individual buildings that are then extrapolated to represent the entire building stock by means of weighting coefficients. Data used as input for bottom-up models include building properties such as geometry, U-values of individual components, climate data, indoor temperature requirements and equipment use. In addition to the modelling of the energy use, when assessing development options the inclusion of a life-cycle assessment is important and has been identified as lacking in exiting analysis tools [6]. A recent development is spatial building stock modelling (SBSM) where GIS data is included which has been used for analyzing of energy policy scenarios in an urban context [7], assessing the heat island effect on energy demand [8] and identifying and testing sustainable energy targets for building stocks [9].

The aim is to develope a methodology focusing on urban areas and to incorporating GIS data to account for the distribution of buildings in specified areas within the urban setting as well as to facilitate illustration of the results. The methodology is also expanded with a life-cycle perspective through LCA to account for environmental impacts of the development strategies. The main advantage of incorporating GIS in BSM is that not only can the model be used to evaluate different technological solutions to improve energy efficiency and reduce greenhouse-gas (GHG) emissions associated with the building stock but also to provide a link between the building statistics and the spatial location of the different building types within the urban setting. The inclusion of a life-cycle assessment when evaluating the environmental impacts of refurbishment options is important as it obviously otherwise leads to an overestimation of the environmental gains and lead to sub-optimized development strategies.

Methodology

This work takes departure in a previously developed building stock model (ECCABS [10]) which was successfully applied to evaluate the potentials and costs of different Energy Conservation Measures (ECMs) applied to building stocks of different European countries [11].The ECCABS building stock model represents a framework that allows a combination (or choice) of different assessments at a reference-building level to be extrapolated to the building-stock level for a different combination (or choice) of outputs. The assessment at the building level currently includes energy use, indoor air environment, technical building systems, and some on-site generation based on renewable energy systems. The variety of outputs is presently tailored for investigations of indoor environment, energy system issues, climate change mitigation, and policy targets. The ECCABS building stock model applies archetype buildings for representing the existing building stock. The archetypes are obtained from four steps [12]: *segmentation* (in which the number of archetypes building is decided), *characterization* (in which the physical and technical properties of each archetype are described), *quantification* (in which so-called weighting coefficients are calculated, that represent the amount of buildings in the stock equal to each archetype) and *validation* of the final energy demand in the building stock for a reference year. To validate the building stock aggregation, the final energy demand is modelled using defined archetype buildings as input to the model and comparing the results with corresponding values of energy use found in national and international statistics for a particular reference year.

Spatial distribution

The quantification used in the above mentioned methodology is adapted to GIS data instead of using weighting based on statistical data. In the methodology developed the archetypes are spatially distributed by matching them to actual buildings. This requires data regarding the spatial distribution of buildings within an area with adequate information so as to link the buildings to an archetype building previously created. The ambiguous term “area” can refer to different spatial resolutions ranging from individual neighborhoods to entire countries or larger regions such as the European Union (EU). The information needed includes spatially referenced floor area, building type and construction period. It is necessary to utilize multiple data sources to distribute the buildings according to the archetype buildings created for which GIS is used. The most basic form of geometry available in GIS-maps at a building level is the footprint. As the total heated floor area (HFA) is needed for simulations, the height of the building or the number of floors needs to be specified. For the case of Gothenburg, building geometry, including the height of each individual building is provided from the City planning office of Gothenburg [13] while building age and type is obtained from the property register.

A previously developed spatial BSM within the Smart Urban Adapt (SUA) project uses a method where building geometry is specified for the archetype buildings using GIS-maps to specify output area specific archetypes [7]. This reduces the computational time as each building is represented by an average geometry based on its archetype while still retaining the correct geometry and HFA of the total amount for each arhcetype within the desired output level. The reduction in accuracy of using an average geometry compared to using each individual building’s geometry been calculated and shows large deviations on a building level [14]. To ensure the robustness of the results and to enable an evaluation of which development strategies are suitable for specific buildings, the geometry of each individual building is modeled.

Model validation and adjustment

As data may not be available regarding all parameters of the archetypes, the assumptions done to overcome this issue need to be verified and adjusted. This is carried out by comparing measured data to results from the simulated energy demand. For this purpose several datasources are available. Data from energy performance certificates (EPC), which for Sweden is based on measured energy use, is used to adjust assumptions in the model. The EPCs are provided by the Swedish National Board of Housing, Building and Planning [15]. The EPC data contains spatially referenced information regarding measured energy use for heating, hot water and property electricity as well as heated floor area, technical systems and number of stories [15]. A second datasource for the measured energy use can be retrieved directly from the energy supply company with the consent from the property owner. This information is used to validate that the archetype used to represent a particular building is reasonable and to make adjustments where needed. The need to adjust the initial assumptions regarding the technical state of a building stems from the fact that the current status of the building is often not known. That is, past refurbishment may not be known as no official data has been collected. Figure 1 below shows a simplified flowchart of the modeling procedure and what data is included in the different parts as well as the iterative role of measured data. A sensitivity analysis is performed as to determine to which degree the assumptions regarding the technical state of the archetypes influence the model and its outcome, and especially in connection to the with LCA analysis (see below).

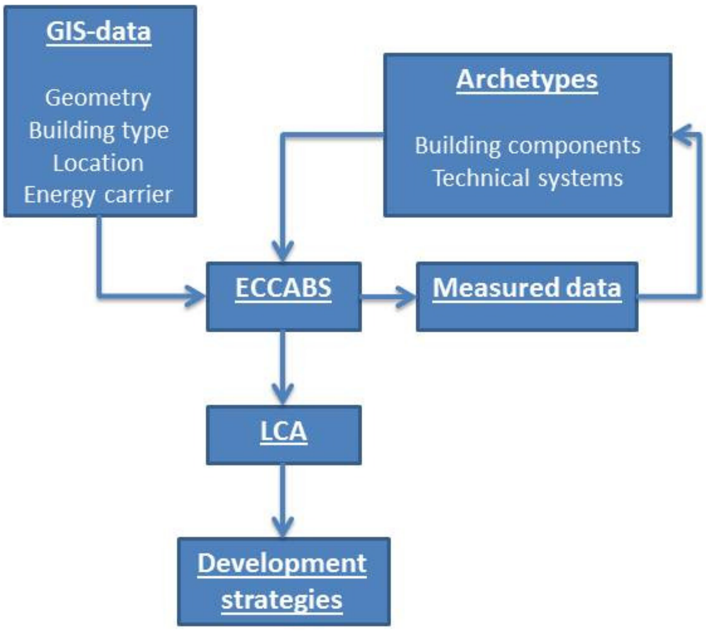

Figure 1 Simplified modeling flowchart

Life-cycle assessment

The goal of the LCA component is to:

a) Convey that energy optimisation of the operation during the lifetime of a building might have an "environmental cost" that has to be payed in terms of the use of natural resources, emissions, and waste due to the production of a construction material or the shift towards another energy carrier.
b) Show environmental impacts over the entire life-cycle considering a spectrum of impact categories and not only GHG emissions or a reduced final or primary energy demand for different development strategies.
c) Show large property owners how to make priorities from a more extensive environmental point of view within their specific building portfolio in order to develop this further with regards to what buildings to target and what measures to take (refurbishment, new buildings, replacement buildings, additional top units, change of energy supply system).

To achieve this, the starting point is an accounting type LCA for the baseline model of the building stock. Development scenarios for refurbishment, add-ons and new construction are evaluated with respect to their environmental impact over the life-time of the buildings. As one aim of the LCA is to to avoid-suboptimizing in the development strategies, the environmental impact not only during the operation of the building but also the construction and end-of-life including the manufacturing and transport of building material is considered. Avoiding sub-optimization provides a possibility to do more with less which may also result in a more economicly feasible solution. For existing buildings the geometry is known and as such the amount of material needed for development strategies such as added wall insulation can be calculated (in our case with the ECCABS model). Using a spatial component for all buidlings enables the modelling of local energy supply mixes. Information regarding energy and resource use as well as emissions in material manufacturing processes and the amount of material needed for development strategies together with knowledge regarding emissions resulting from the energy supply mix and waste management options forms the foundation for the LCA. The functional unit is HFA and geographic boundaries are limited to those of the City of Gothenburg. All processes regarding construction materials is considered, i.e from extraction of raw materials over manufacturing to on-site assembly and lastly end of life options, including all transport occurring between the different life cycle phases. As the geographic boundaries are set to the City of Gothenburg, the local mix for district heating is applied while electricity is based on a national production mix with regards to emissions. Initially the following impact categories are considered in the LCA, although this will be developed in collaboration with stakeholders:

- Global warming potential (GWP)
- Abiotic depletion potential (ADP)
- Acidification
- Eutrofication
- Ozone depletion potential (ODP)
- Human toxicity potential (HTP)
- Ecotoxicity

To continue from impact categories to a weighting index has both advantages and disadvantages. It is easier to convey the results of a LCA as an aggregated index, and depending on the target audience it may be preferable to do so. On the other hand, weighting methods are to some degree based on value-choices and are not scientifically based [15]. If a weighting method is used, it is important to compare results from several methods to ascertain the robustness of the modelling results. As both the energy demand side calculations as well as parts in the LCA are subject to uncertainty, a Monte-Carlo based sensitivity analysis is performed to distinguish what parameters have a large influence on results and to assess the statistical likelyhood of development strategies having a positive environmental impact. At present, there is a lack of consensus regarding how the choice of energy mix for the energy carriers used in the building sector should be handled and as such, the impact of using a marginal as well as an average approach is determined in the sensitivity analysis to ensure the robustness of the results. A dominance analysis where the environmental impact of each building in the stock is compared is conducted to distinguish what buildings have the largest environmental impacts as to make priorities for refurbishment options.

One possibility from applying the LCA in connection with GIS is that it makes possible a local impact assessment. As the modelling is performed on a local scale with a local dataset, the impact of emissions can be evaluated on a local level. To further enhance this possibility, GIS can be used to visualize the local impact of different development strategies which may help in conveying the results to stakeholders.

Conclusions

We have presented an initial modeling work with the aim to develop a methodological framework for spatial modelling of energy and resource use of buildings in urbanized areas. The methodology is based on integration of LCA and GIS analysis with anexisting building stock modelling framework (ECCABS).

The next step is to complete the development of the modeling and apply it to a case study for the City of Gothenburg (Sweden). We then expect to identify key issues in the steps required for building stock aggregation, especially with respect to providing a building stock aggregation which facilitates a relevant LCA analysis.

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